Final Report

NAG2-1124: Measurements of Long-Lived Trace Gases from Commercial Aircraft Platforms: Development of Instrumentation

Project Goal: The upper troposphere (6 - 12 km altitude) is a poorly understood and highly vulnerable region of the atmosphere. It is important because many trace species, including ozone, have their greatest impact as greenhouse (infrared-absorbing) gases in this region. The addition of relatively small amounts of anthropogenic chemicals, such as nitrogen oxides, can have a dramatic effect on the abundance of ozone. Some of these pollutants are deposited directly, e.g., by aircraft, while others are transported in. The primary goal of this project was to measure several chemical compounds in the upper troposphere that will help us to understand how air is to transported to that part of the atmosphere; that is, does it come down from the stratosphere, does it rise from the surface via convection, and so on. To obtain adequate sampling to accomplish this goal, we proposed to make measurements from revenue aircraft during normal flight operations.

Funding: This project was supported by the Subsonic Assessment (SASS) component of the NASA Atmospheric Effects of Aviation Program (AEAP), whose mandate is to study how the current fleet of aircraft has affected and continues to influence the upper troposphere and lower stratosphere. Additional funding was provided by the EPA's Early Career Award program toward the development of one component of the experiment.

Uniqueness: The approach taken in this project is unique for a number of reasons. First, no other research group in the United States is using revenue aircraft as sampling platforms for atmospheric chemical constituent measurements. The European Community has a similar, highly successful project to observe ozone and water vapor from in-service aircraft, called MOZAIC. Second, it is typical for observations of multiple chemical species to be made by multiple individual instruments. This is expensive, as each institution requires monetary support and each instrument has its own data system, plumbing, inlet, etc. For an aircraft, weight translates directly to fuel requirements, which translates to cost. Our project represents a departure from this approach. We proposed to fly four different sensors with common inlet, plumbing, and computer control system, resulting in a low-cost, relatively lightweight package. All components together weigh less than 250 lbs.

Milestones: Funding for this instrument development project was first received in mid-1997. After six months of design work, a preliminary design review (PDR) was held to determine whether the project should go forward. The outcome of the PDR was positive, so the instrument development proceeded with some relatively minor changes. The first completed component, a water vapor sensor (hygrometer), was delivered in fall 1998 and test-flown on the NCAR C-130 aircraft. The ozone sensor and prototype computer system were completed in spring 1999 and tested during the Carbon Dioxide Budget and Rectification Airborne (COBRA) field mission in June 1999. The remainder of the instrumentation was built during the summer and early fall of 1999, and installed on the

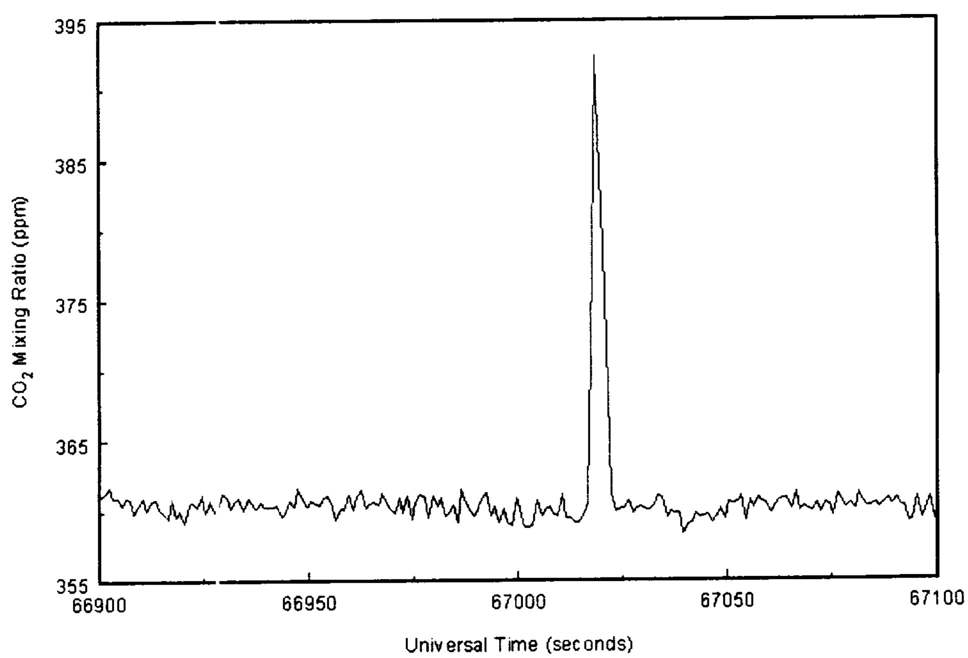
NASA DC-8 aircraft for the SAGE III Ozone Loss and Validation Experiment (SOLVE), held during winter 1999/2000. In addition to serving as a proof-of-concept for the TOTCAP package, this mission provided an opportunity to gather science-quality data. Following laboratory calibrations in spring and summer 2000, the SOLVE data was submitted to the mission data archive and is being analyzed by graduate students as part of their Ph.D. theses.

Personnel Supported: Funding from this grant supported the work of several students, scientists, and engineers over the duration of the project. Dr. Barkley Sive began working on this project after completing his doctorate at the University of California, Irvine under Profs. Sherwood Rowland and Donald Blake (who also served as a consultant on this project). Dr. Sive designed and built a laboratory test facility for development of the gas chromatograph (GC) and was responsible for the operation of the GC during field studies. Dr. Leah Goldfarb worked on this project after completing her graduate work at the University of Colorado. She completed several tests related to the ozone sensor that ultimately led to it's construction based on a commercial optical bench. Graduate students Erin Whitney and Amelia Gates were also supported by this project. Ms. Whitney was responsible for calibration of the water vapor sensor and participated in the SOLVE campaign. Ms. Gates has been working with collaborator Prof. Darin Toohey (University of Colorado) on the development and testing of a carbon dioxide sensor. She has participated in several field experiments with this instrument and is expected to complete her Ph.D. in autumn 2002. Sarah Thompson, an undergraduate physics major, worked in the laboratory for a summer and the following fall semester. She assisted Dr. Sive with the development of the flight GC.

Design and fabrication of the ozone and carbon dioxide sensors, power supply and computer have been overseen by Gregg Allison (electrical/software engineer) and Zach Castleman (mechanical engineer). We also employed at various times two machinists and two electrical assembly technicians from among LASP's staff. [The Laboratory for Atmospheric and Space Physics (LASP) has a large staff of engineers, technicians and research associates who work on in-house projects on an as-needed basis. The availability of such resources significantly reduced the personnel budget for a project such as this, which required much less than full-time support from a few specialty services.] In addition, Dr. Hiro Kosai was employed on a temporary basis to design several specific circuit boards for the instrument package. Dylan Yaney, an undergraduate mechanical engineering major, worked part-time during one semester and full-time over a summer creating parts drawings and repackaging the water vapor sensor for deployment on the NASA DC-8.

Instrumentation Developed: In November 1998, the first sensor, a tunable diode laser (TDL) hygrometer was completed. This instrument was purchased from Dr. Randy May of JPL and Maycomm Research. We gained some flight experience with the TDL on the NCAR C-130 during two test flights from Jefferson County Airport outside of Boulder. The instrument performed flawlessly.

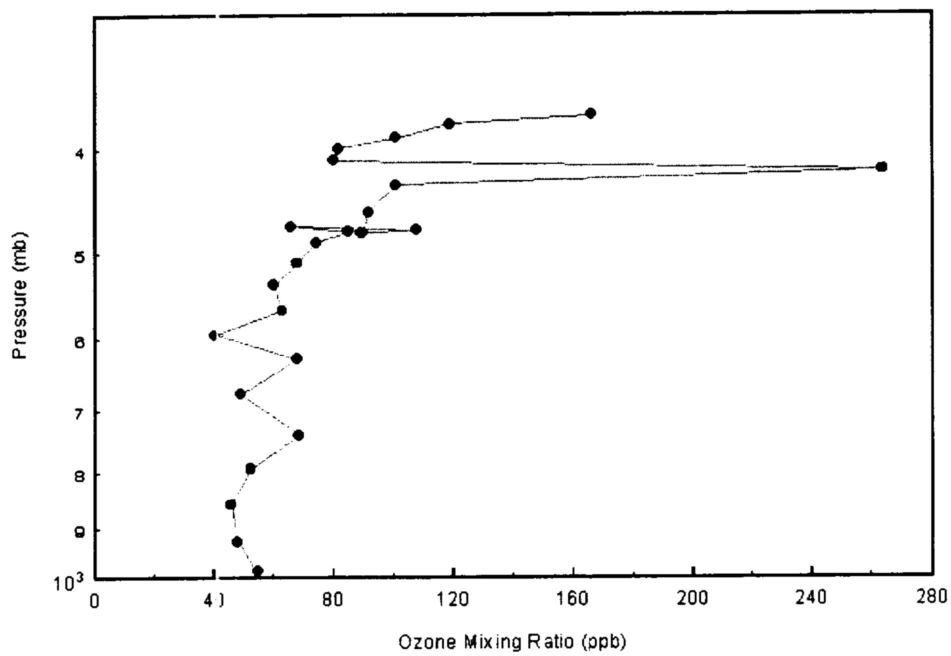
In March and April 1999, Ms. Gates and Prof. Toohey assembled a prototype of the carbon dioxide sensor and flew it on the NASA WB-57 aircraft during the rocket-intercept phase of the Atmospheric Chemistry of Combustion Emissions Nearth the Tropopause (ACCENT) mission. In order to measure carbon dioxide accurately, it is important that the pressure and temperature within the instrument both remain constant to about 1 part in 3000. This requires a number of control/feedback loops, particularly for pressure, which were tested successfully on the WB-57 flights. Pressure control and detection sensitivity are enhanced if the instrument is fed with air compressed above ambient pressure (which, for the WB-57, drops to 60 mb at cruise altitude). A single-stage compressor is employed for the overall package to provide high-pressure (1060 mb) air to both the gas chromatograph and carbon dioxide instruments. Carbon dioxide data obtained on one of the rocket intercept flights is shown below. Both the prototype and the final instrument were flown on the NCAR C-130 in April 2002 as part of a flight series dedicated to sensor development. The data obtained on that project will serve as the basis for instrument modifications to enable future measurements in the atmospheric boundary layer.



Carbon dioxide measurement through the plume of an ATLAS rocket at 65,000 ft.

The ozone sensor was completed and, along with a new computer/data acquisition system and power supply, was flown for 18 hours onboard the University of North Dakota Cessna Citation in early June 1999. The PI was approached by Prof. Steven Wofsy of Harvard University to fly this instrument as part of the CO_2 Budget and Rectification

Airborne Study (COBRA), a program designed to assess the regional fluxes of carbon dioxide from various ecosystems. Ozone serves as a tracer of the boundary layer and potentially, of influx of polluted air to the study site. An example of preliminary data is shown below.

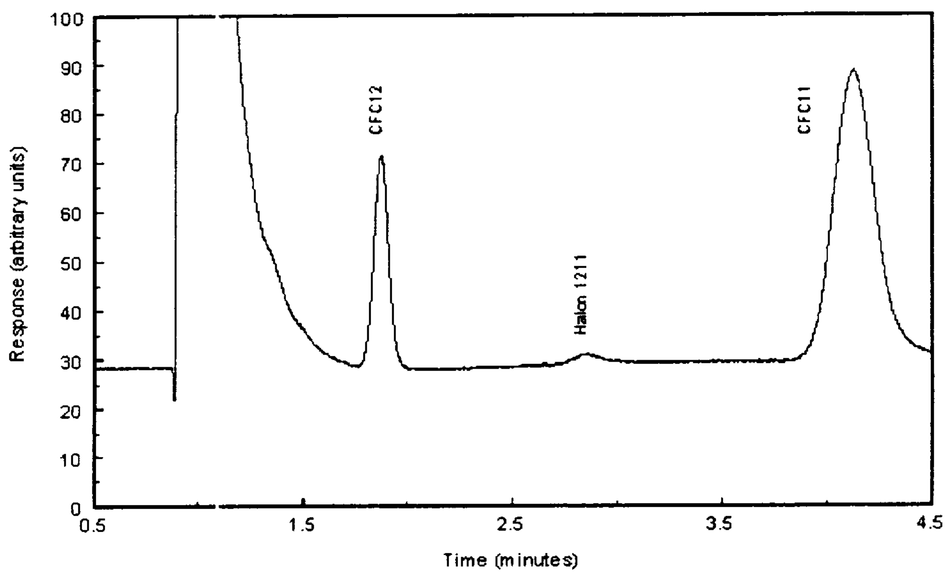


Ozone data from a profile over Grand Forks, ND on 5 June 1999.

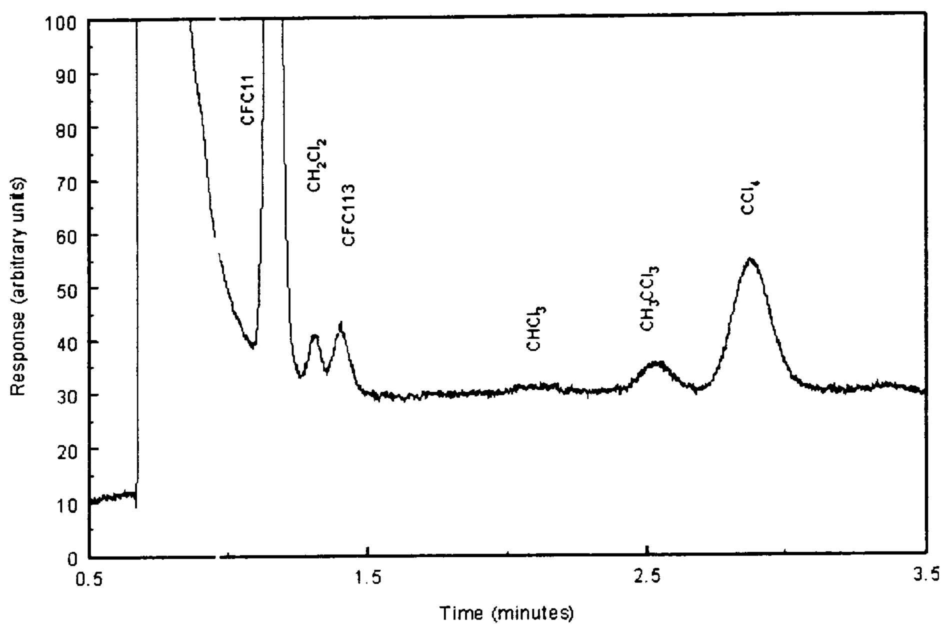
In January 1999, the PI was asked by the Subsonic Assessment program scientist (Don Anderson) about the possibility of flying the instrument package on the NASA DC-8 during the SAGE III Ozone Loss and Validation Experiment (SOLVE). This seemed feasible and, since no progress had been made in finding a commercial carrier for the payload, an opportunity to demonstrate the capabilities of the package. In particular, we contributed measurements of a number of halocarbons, which have been used to assess the amount of organic chlorine present, as well as to study cross-tropopause transport. We are also using our water measurements, along with those made by a similar, open-path sensor, to assess the abundance of condensed-phase water in cirrus clouds.

To accommodate the scientific goals of SOLVE, we altered the proposed design of our gas chromatograph. Originally, it was our intent to make continuous measurements of a single halocarbon, tetrachloroethene (C_2Cl_4), which is an excellent tracer of surface air. This would have been accomplished by constructing a paired set of chromatographic columns and detectors and constantly running an ambient sample and a standard - one on each column. Switching valves would have alternated the sample and standard from one column to the other. Instead, made use of the two channels of the instrument to measure a wider variety of gases, and ran a standard gas through both channels every thirty minutes. Example chromatograms from SOLVE are shown below, illustrating some of the gases we may measured. These data are being used by other SOLVE investigators to study chlorine chemistry in the lower stratosphere and upper troposphere.

Outlook: With the aid of program management at NASA, we have engaged in discussions with several airlines and an aircraft manufacturer about carrying the TOTCAP package. To date, none of these have agreed to fly the instrumentation. We expect that it will take five to ten years to find a long-term carrier for the TOTCAP package. Meanwhile, individual instruments will be used in other field experiments as opportunity arises. For example, the TDL hygrometer will fly on the NASA WB-57F aircraft during the CRYSTAL-FACE mission in summer 2002.



Chromatogram from Channel 1 showing CFCs -11 and -12 and Halon 1211; first broad peak is air.



Chromatogram from Channel 2, showing CFCs -11 and -113 and a number of other chlorocarbons; first peak is air.

Media:

"Sky Sensors", interview on The Osgood Files, CBS radio, 14 August 2001.

"Sky Sensors", wire story from The American Communications Foundation.

Publications:

A.G. Hallar, L.M. Avallone, R. L. Herman and B. Anderson, Observations of "total water" from the NASA DC-8 during SOLVE: Implications for cloud water content, to be submitted to *J. Geophys. Res.*, 2002.

B. F. Thornton, L. M. Avallone, D. W. Toohey, H. Harder, M. Martinez, J. Simpas, and W. H. Brune, Observations of ClO near the arctic tropopause in winter, to be submitted to *J. Geophys. Res.*, 2002.

A.M. Gates, High Resolution Measurements of Carbon Dioxide in the Upper Troposphere and Lower Stratosphere, Ph.D. thesis, University of Colorado.

Invited Talks and Seminars:

Autonomous Instrumentation for Measurements of Trace Gases from Commercial Aircraft Platforms, invited talk, Federation of Analytical Chemistry and Spectroscopy Societies, Providence, RI, 30 October 1997.

Autonomous Instrumentation for Measurements of Trace Gases from Commercial Aircraft Platforms, Earth System Science seminar, University of California at Irvine, 26 November 1997.

Autonomous Instrumentation for Measurements of Trace Gases from Commercial Aircraft Platforms, Meteorology seminar, University of Maryland, 5 January 1998.

Development of Instrumentation for Measurements from Commercial Aircraft, NOAA Aeronomy Lab seminar, 4 March 1998.

Assessing the Role of Dynamics in Tropospheric Chemistry: Measurements from Commercial Aircraft Platforms, invited talk, Telluride Summer Research Workshop on Uncertainties in Tropospheric Chemistry, 7 August 1998.

TOTCAP: Tropospheric Ozone and Tracers from Commercial Aircraft Platforms, Laboratory for Atmospheric and Space Physics seminar, University of Colorado, 24 September 1998.

TOTCAP: Tropospheric Ozone and Tracers from Commercial Aircraft Platforms, Program in Atmospheric and Oceanic Sciences seminar, University of Colorado, 2 October 1998.

Understanding Atmospheric Ozone: Measurements from Balloons and Aircraft, Laboratory for Atmospheric and Space Physics, University of Colorado, seminar for non-scientists, 21 October 1998.

The Tropospheric Ozone and Tracers from Commercial Aircraft Platforms (TOTCAP) Instrumentation: First Results, NASA Ames Earth Science Seminar, 10 August 2000.

Trace Gas Observations at the High Latitude Winter Tropopause with a New Aircraft Instrument, Atmospheric and Oceanic Sciences Seminar, University of Wisconsin, 31 October 2000.

Trace Gas Observations at the High Latitude Winter Tropopause with a New Aircraft Instrument, Program in Atmospheric and Oceanic Sciences seminar, University of Colorado, 17 November 2000.

Measurements in Arctic Cirrus and Rocket Plumes: New Insights into Particle Sizes and Composition, Program in Atmospheric and Oceanic Sciences seminar, University of Colorado, 14 November 2001.

In situ measurements in rocket plumes and arctic cirrus: New insights into particle size and composition, Scripps Institute of Oceanography Climate Seminar, 21 March 2002.

In situ measurements in rocket plumes and arctic cirrus: New insights into particle size and composition, Laboratory for Atmospheric and Space Physics seminar, University of Colorado, 24 April 2002.

Presentations at Meetings:

L. M. Avallone, *A proposal to develop instrumentation for measurements from commercial aircraft*, poster presented at the Atmospheric Effects of Aviation Annual Meeting, Virginia Beach, VA; March 1997.

L. M. Avallone, *Instrument development for measurements from commercial aircraft*, poster presented at the IGAC/SPARC/GAW Conference on Global Measurement Systems for Atmospheric Composition, Toronto, Canada; May 1997.

E.S. Whitney and L.M. Avallone, *Atmospheric water vapor measurements in the upper troposphere using a tunable diode laser hygrometer*, poster presented at the ASTAIRE Workshop on Atmospheric Effects of Aircraft in the Upper Troposphere and Lower Stratosphere, Bergen, Norway; August 1999.

L.M. Avallone, D.R. Blake, A.M. Gates, R.D. May, B.C. Sive, D.W. Toohey, and E.S. Whitney, *The Tropospheric Ozone and Tracers from Commercial Aircraft Platforms (TOTCAP) Instrumentation: First Results*, poster presented at the 2000 Atmospheric Effects of Aviation Annual meeting, Snowmass, CO, June 2000.

L.M. Avallone and A.G. Hallar, *Trace gas correlations in the tropopause region as observed from the NASA DC-8 during SOLVE*, talk and poster presented at the SOLVE-THESEO Science Team Meeting, Palermo, Italy, September 2000.

A.M. Gates, L.M. Avallone, D.W. Toohey and S. A. Vay, *The Tropospheric Ozone and Tracers from Commercial Aircraft Platforms (TOTCAP) carbon dioxide measurement during the SOLVE campaign: Data comparison and a dynamical study*, poster presented at the SOLVE-THESEO Science Team Meeting, Palermo, Italy, September 2000.

E.S. Whitney, L. M. Avallone, J.R. Podolske, R. Herman, G. Sachse, E. Jensen, R. D. May, and B. Anderson, *An examination of "total water" measurements from a closed-path tunable diode laser hygrometer aboard the NASA DC-8 aircraft during the SOLVE campaign*, poster presented at the SOLVE-THESEO Science Team Meeting, Palermo, Italy, September 2000.

B. Thornton, L. Avallone, W. Brune, D. Toohey, H. Harder, M. Martinez-Harder, and J. Simpas, *Latitudinal and seasonal variability of ClO in the lowermost stratosphere*, poster presented at the Fall American Geophysical Union Meeting, San Francisco, CA, December 2000.

L.M. Avallone, A.M. Gates, and A.G. Hallar, *Trace gas correlations near the high-latitude tropopause with measurements from a new suite of instruments*, talk presented at the Spring American Geophysical Union Meeting, Boston, MA, May 2001.

B. Thornton, D. Toohey, L. Avallone, H. Harder, M. Martinez, J. Simpas, W. Brune, M. Avery, E. Richard, and M. Proffitt, *In situ measurements of ClO near the tropopause*, poster presented at the European Geophysical Society Meeting, Nice, France, April 2002.